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The Tethered Moon

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A reasonable initial condition on Earth after the Moon-forming impact is that it begins as a hot global magma ocean[1,2]. We therefore begin our study with the mantle as a liquid ocean with a surface temperature on the order of 3000-4000 K at a time some 100-1000 years after the impact, by which point we can hope that early transients have settled down. A 2nd initial condition is a substantial atmosphere, 100-1000 bars of H2O and CO2, supplemented by smaller amounts of CO, H2, N2, various sulfur-containing gases, and a suite of geochemical volatiles evaporated from the magma. Third, we start the Moon with its current mass at the relevant Roche limit. The 4th initial condition is the angular momentum of the Earth-Moon system. Canonical models hold this constant, whilst some recent models begin with considerably more angular momentum than is present today.

Here we present a ruthlessly simplified model of Earth's cooling magmasphere based on a full-featured atmosphere and including tidal heating by the newborn Moon. Thermal blanketing by H2O-CO2 atmospheres slows cooling of a magma ocean. Geochemical volatiles - chiefly S, Na, and Cl - raise the opacity of the magma ocean's atmosphere and slow cooling still more. We assume a uniform mantle with a single internal (potential) temperature and a global viscosity. The important "freezing point" is the sharp rheological transition between a fluid carrying suspended crystals and a solid matrix through which fluids percolate. Most tidal heating takes place at this "freezing point" in a gel that is both pliable and viscous. Parameterized convection links the cooling rate to the temperature and heat generation inside the Earth. Tidal heating is a major effect. Tidal dissipation in the magma ocean is described by viscosity. The Moon is entwined with Earth by the negative feedback between thermal blanketing and tidal heating that comes from the temperature-dependent viscosity of the magma ocean. Because of this feedback, the rate that the Moon's orbit evolves is limited by the modest radiative cooling rate of Earth's atmosphere, which in effect tethers the Moon to the Earth. Consequently the Moon's orbit evolves orders of magnitude more slowly than in conventional models. Slow orbital evolution promotes capture by orbital resonances that may have been important in the Earth-Moon system